A Grouping Model for Distributed Pipeline Assets Maintenance Decision

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***Abstract*—Distributed pipeline assets systems are crucial to society. The deterioration of these assets and the optimal allocation of limited budget for their maintenance correspond to crucial challenges for water utility managers. Decision makers should be assisted with optimal solutions to select the best maintenance plan concerning available resources and management strategies. Much research effort has been dedicated to the development of optimal strategies for maintenance of water pipes. Most of the maintenance strategies are intended for scheduling individual water pipe. Consideration of optimal group scheduling replacement jobs for groups of pipes or other linear assets has so far not received much attention in literature. It is a common practice that replacement planners select two or three pipes manually with ambiguous criteria to group into one replacement job. This is obviously not the best solution for job grouping and may not be cost effective, especially when total cost can be up to multiple million dollars. In this paper, an optimal group scheduling scheme with three decision criteria for distributed pipeline assets maintenance decision is proposed. A Maintenance Grouping Optimization (MGO) model with multiple criteria is developed. An immediate challenge of such modeling is to deal with scalability of vast combinatorial solution space. To address this issue, a modified genetic algorithm is developed together with a Judgment Matrix. This Judgment Matrix is corresponding to various combinations of pipe replacement schedules. An industrial case study based on a section of a real water distribution network was conducted to test the new model. The results of the case study show that new schedule generated a significant cost reduction compared with the schedule without grouping pipes.**

I. INTRODUCTION

The deterioration of distributed pipeline assets and the optimal allocation of limited budget for maintenance correspond to crucial challenges for water utility managers. Choosing optimal solutions with the best maintenance plans concerning available resources is a crucial problem for decision makers. This problem is generally expressed as, "For a water distribution network of N individual pipes with an inventory of general information such as length, diameter, material, soil type, zone area, and GIS information, given a replacement planning horizon of T years, how should the pipes be replaced on order to maximize economic utility?" The "Pipe" is defined as a part of pipeline from one node to another node (manhole, network junction, etc) in the water network.

Most of maintenance decision model in current research only considered individual pipes [1--3]. The consideration of pipe grouping in planning replacement jobs for water distributed pipelines, has so far not received much attention in the literature. However, from the water utilities owner's point of view, grouping can certainly reduce the cost of replacement. In current practice, replacement planners usually select two or three pipes manually with ambiguous criteria to group as one replacement job. This practice is often not the best solution for pipe grouping and not cost effective, so that it is not a viable solution for planners. To address this issue, a novel concept of group scheduling are introduced, and a Maintenance Grouping Optimization (MGO) model is developed in this paper to help distributed pipeline assets owners and operators make scheduling decisions for replacement of water pipes.

II. SCHEME OF GROUP SCHEDULING

A. Group Scheduling for Pipeline Maintenance

Group scheduling for pipeline maintenance: *when a collection of individual pipes are scheduled for replacement, a buck of pipes are taken into account and united into a group with certain criteria*. In other words, replacement can be done in groups of pipes rather than on an individual pipe.

B. Three Criteria for Group Schedulling

1) Grouping with geographically adjacent pipes

If two pipes are adjacent each other geographically, they might be grouped. Pipes' location information provided by Geographic Information System (GIS) of Water distribution network is needed, which integrates: *a)* geographical coordinates of each node of pipes; *b)* geographical coordinates of each work station; and *c)* road map of the area where pipes located. This information determines on the travel cost of replacing each pipe.

2) Grouping with identical unique replacement machinery

Pipes might be grouped on account of using the same unique replacement machinery. It might be cost effective that some similar replacement jobs share the same unique machinery and teams especially for large diameter pipes. This criterion needs general information of each pipe such as diameter, material and length.

3) Grouping with similar customer interruption

If the interruption areas of two pipes are partly overlapped, there are two circumstances: *a)* only one team replaces the two pipes In this case, the interruption time is equal to the sum of the replacing time of these two jobs; *b)* two teams replace the two pipes separately. In this case, the interruption time is equal to the longer replacing time. It is reasonable to assume that the impact of customer interruption for the second circumstance is much smaller, but the cost for human resource is higher than the first one. The impact of customer interruption can be quantified according to the customer numbers, customer types and interruption hours.

C. Judgment Matrix

Following the three criteria, a Judgment Matrix Λ is defined for illustrating the grouping relationship among pipes:

$$\Lambda = \begin{bmatrix} \varepsilon_{11} & \cdots & \varepsilon_{1j} & \cdots & \varepsilon_{1n} \\ \vdots & \ddots & \vdots & & \vdots \\ \varepsilon_{i1} & \cdots & \varepsilon_{ij} & \cdots & \varepsilon_{in} \\ \vdots & & \vdots & \ddots & \vdots \\ \varepsilon_{n1} & \cdots & \varepsilon_{nj} & \cdots & \varepsilon_{nn} \end{bmatrix} \quad (1)$$

Where $\mathcal{E}_{ij} = \begin{cases} 1, \text{ grouping } i,j \\ 0, \text{ otherwise} \end{cases}$, $i, j, n \in N$, i, j, n are the indexes of pipe, and N is the total number of pipes in the network.

1) To filter adjacent pipes:

For a pipeline network, geographic information *(geographical coordinates)* of each item *(pipe, node, workstation, valve, pump, etc)* can be known from Geographic Information System (GIS). As a pipe is a linear asset, we could not decide its exact geographical coordinates. Therefore, to tackle this problem, geographical coordinates of the central point of the two nodes connected with the pipe is used as the geographical coordinates of one pipe.

To determine which pipes are close to target pipe i, γ_{ij} and $\gamma^*$are defined:

γ_{ij}= Geographic distance from pipe i to pipe j (km);

γ^*= Maximum geographic distance (km);

If $\gamma_{ij} \le \gamma^*$, then pipe j belongs to the adjacent pipes of pipe i;

The Judgment Matrix Λ for adjacent pipes is:

$$\mathcal{E}_{ij} = \begin{cases} 1, \ \gamma_{ij} \le \gamma^* \\ 0, \ \text{otherwise} \end{cases} \quad (2)$$

Where $\mathcal{E}_{ij}$=1 illustrates each adjacent pipe of pipe i.

2) To filter pipes with identical unique replacement machinery:

Replacing different types of pipes (materials, diameters, soil types, etc) may need different replacement technologies with different machinery and costs. Define U_i is the machinery used for replacement pipe i, and the Judgment Matrix Λ for identical unique replacement machinery is:

$$\mathcal{E}_{ij} = \begin{cases} 1, \ U_i = U_j \\ 0, \ \text{otherwise} \end{cases} \quad (3)$$

where U_i and U_j need expert knowledge to decide.

3) To filter pipes with similar areas of customer interruption:

A hydraulic model is utilized for locating which nodes *(junction and customer)* are interrupted by replacement jobs, through calculating the nodal flow discontinuity by EPANET2 [4]. Once locating the nodes number, the nodes data for each replaced pipe i can be stored. Then a filter can exclude the junction nodes and remain customer nodes. The number of customer nodes interrupted by replacing pipe i, pipe j are defined as N_i and N_j, and their overlapping number is defined as N_{ij}. Define η:

$$\eta = \frac{N_{ij}}{N}, \ N = \begin{cases} N_i, \ N_i \le N_j \\ N_j, \ \text{otherwise} \end{cases} \quad (4)$$

The Judgment Matrix Λ for similar customer interruption is:

$$\mathcal{E}_{ij} = \begin{cases} 1, \ \eta \ge \eta^* \\ 0, \ \text{otherwise} \end{cases} \quad (5)$$

Where $\eta^*$is a judgment value, which depends on the total number of customers.

III. Maintenance Grouping Optimization Model

The entire procedure of the Maintenance Grouping Optimization model is illustrated in the Fig 1. The information necessary for the proposed model includes *a)* general information of the whole network such as material, length, and diameter of each pipe; *b)* GIS information such as pipes, nodes, roads, and customers; *c)* Hydraulic information such as pressure and volume of flow; *d)* Maintenance history information such as age, repair date, duration of repair and repair cost); *e)* Expert knowledge such as maintenance standards and techniques.

The model, generally, contains two parts *a)* pre-analysis and *b)* grouping analysis. The pre-analysis aims to obtain the targeted pipes that are needed to replace during a planning horizon T. In this process, all pipes in the network should be analyzed through calculating the total cost C^{tot}, and using optimization techniques to find the optimum replacement year t^* of each pipe. The pipes with t^* located in the planning horizon T are stored in a database for the grouping analysis. The grouping analysis aims to discover the optimum group scheduling for pipes replacement. This process starts with a calculation of the distance for each pipe in the selected pipes from pre-analysis process. Simultaneously, a hydraulic model and expert knowledge are used to determine the pipes with identical replacement machinery and similar customer interruption. These practices are intended to create the

Judgment Matrix Λ. Then a modified replacement cost formulation is used to calculate the total cost of each pipe with the three grouping criteria. Finally, a modified Genetic Algorism with the Judgment Matrix is utilized to search the optimum schedule of grouping pipes with the objective of minimizing the total cost of the whole network during the planning horizon *T*.

A. Total Cost

The total cost C^{tot} associated with pipe replacement is affected by the replacement cost C_i^{repl} and pipeline failures [5]. The cost of pipeline failure includes direct cost with repair cost C^{rep}, direct damage cost C^{dir} and water loss cost C^{wat}, and indirect cost with indirect damage cost C^{indir}, customer service interruption cost C^{inp} and social cost C^{soc}. The present value of the total cost associated with pipe *i* which is replaced in year *t*, with a discount rate *r*, and with the expected number of failure in p^{th} year, $\lambda^*_{i,p}$, is given by:

$$C_{i,t}^{tot} = (C_i^{repl} + C_i^{inp}) \big/ (1+r)^t + \sum_{p=1}^{t} \lambda_{i,p}^{*} [(C_i^{rep} + C_i^{dir} + C_i^{wat} + C_i^{\text{int}errup} + C_i^{indir} + C_i^{soc}) \cdot \frac{1}{(1+r)^p}] \tag{6}$$

B. Replacement Cost

Replacement cost can be affected by the length of replaced pipe, the pipe's diameter, the replacement technologies, and the location of the pipe and work station. The replacement cost function [6] of pipe i, C_i^{repl}, is modified, which divided into three components, cost related to length Cr_i, machinery cost M_i and travel cost Cv_i:

$$C_i^{repl} = Cr_i \cdot l_i + M_i + Cv_i \tag{7}$$

The following two assumptions are made:

1) Only one machinery team is levied if several pipes can form part of the same replacement project, and the machinery cost *M* is given by: $M=M_i$

2) If pipe *i* and pipe *j* are adjacent to each other, and can be combined into one replacement job, the travel cost of the two replacement activities is given by $(Cv_i+ Cv_j)/2+ Cv_{ij}$

where Cv_i is the travel cost from work station to pipe *i*, Cv_j is the travel cost from work station to pipe *j*, Cv_{ij} is the travel cost from pipe *i* to pipe *j*:

$$C_i^{repl} + C_j^{repl} = Cr_i \cdot l_i + Cr_j \cdot l_j + M + (Cv_i + Cv_j)/2 + Cv_{ij} \tag{8}$$

This concept can be extended to *U* adjacent pipes, defined as contiguity *U*, d_i is the travel distance from work station to pipe *i*, thus:

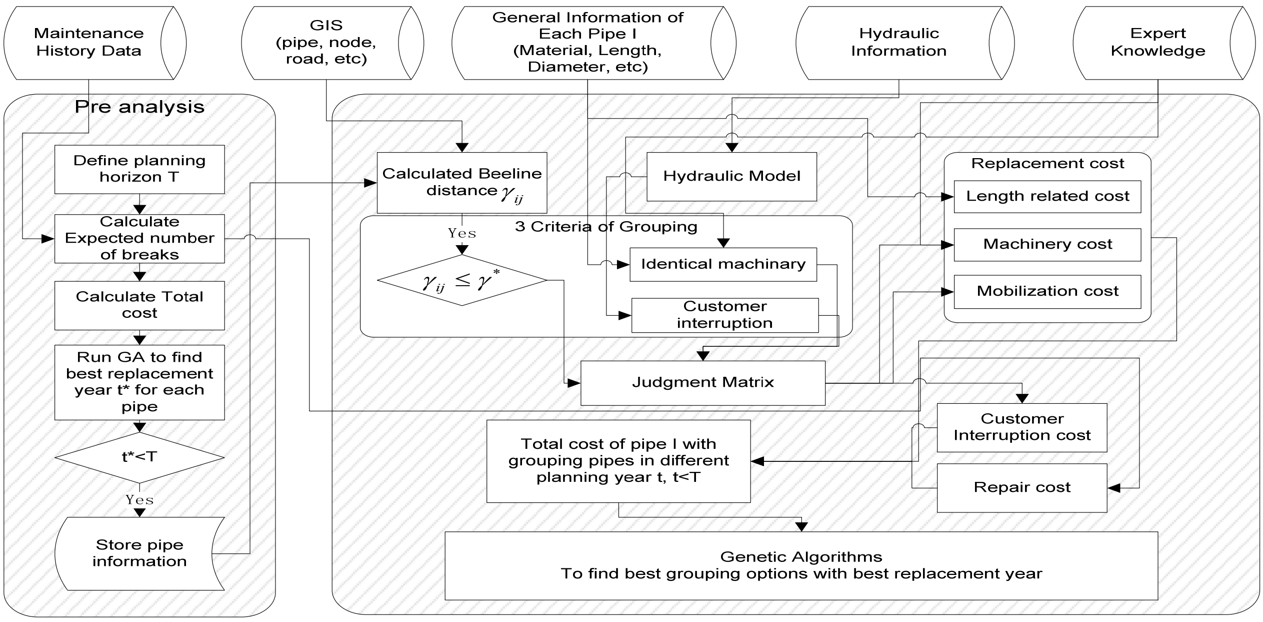

Fig 1: Flowchart of the proposed Maintenance Grouping Optimization model

$$\sum_{\forall i \in U} C_i^{repl} = \sum_{\forall i \in U} (Cr_i \cdot l_i) + M + CV \frac{\sum_{\forall i \in U} (d_i)}{U} \tag{9}$$

The revised replacement cost for pipe *i*, in the t^{th} year, where pipe *i* belongs to contiguity *U*, becomes:

$$C_i^{repl} = \left[\frac{M}{\sum_{\forall i \in U} l_i} + \sum_{\forall i \in U} (Cr_i) \right] \cdot l_i + CV \frac{d_i}{U \cdot \sum_{\forall i \in U} (d_i)} \tag{10}$$

IV. MODIFIED GA MODEL

A. *Objective and Constraints*

1) *Objective*

The objective of the model is to schedule the replacement of candidate pipes during planning horizon T, so as to minimize present value of total cost of water distribution network, taking replacement and failure related costs into account, subject to the three grouping criteria.

The matrix below shows the total cost of each pipe i, whose replacement job will be done in the t^{th} year during planning horizon T.

$$
\begin{array}{cccccc}
 & 1 & \cdots & t & \cdots & T \\
Pipe_1 & C^{tot}_{1,1} & \cdots & C^{tot}_{1,t} & \cdots & C^{tot}_{1,T} \\
\vdots & \vdots & \ddots & \vdots & & \vdots \\
Pipe_i & C^{tot}_{i,1} & \cdots & C^{tot}_{i,t} & \cdots & C^{tot}_{i,T} \\
\vdots & \vdots & & \vdots & \ddots & \vdots \\
Pipe_n & C^{tot}_{n,1} & \cdots & C^{tot}_{n,t} & \cdots & C^{tot}_{n,T}
\end{array}
$$

Therefore, the objective can be transformed to find the minimum system cost during horizon T, C^{tot}_{sys}, which is equal to the minimum cost of sum of the total cost of each pipe i in the selected t^{th} year, $t \in (1,2,\ldots,T)$,

$$Min \quad C^{tot}_{sys} = Min \quad \sum_{\forall t \in T} \sum_{i}^{N} C^{tot}_{i,t} \tag{11}$$

2) *Constraints*

a) The total cost of scheduling pipes replacement during planning horizon T must be smaller than the total budget B_T at this period:

$$\sum_{\forall t \in T} \sum_{i}^{N} C^{tot}_{i,t} \leq B_T \tag{12}$$

b) For Hydraulic model, the flow into the node j Q_j^{in} must be equal to the flow out of that node Q_j^{out}:

$$Q_j^{in} = Q_j^{out} \tag{13}$$

c)For all grouping options, the distance from pipe i to pipe j must be equal or smaller than maximum distance provided:

$$\gamma_{ij} \leq \gamma^* \tag{14}$$

B. *Structure of Modified GA Model*

The genetic algorithm is adapted to the specific problem in a way so as to ensure the convergence satisfied the grouping criteria and to toward the final solution. A directed operation process [7] introduced into genetic operation was modified by using the problem-specific knowledge, the "Judgment Matrix", in order to produce improved offspring. The process was developed to ensure that at each generation, the offspring created are satisfying the grouping criteria. Fig 2 illustrates the basic flow chart of the proposed methodology.

In order to evaluate the performance index of each individual with respect to the objective function, the inversed system cost ($1/C^{tot}_{sys}$) is calculated for each individual. The termination of the program is achieved after attaining a certain user-defined number of iterations, or at the convergence to the solution, which the test of the solution is the *mean fitness/max fitness*.

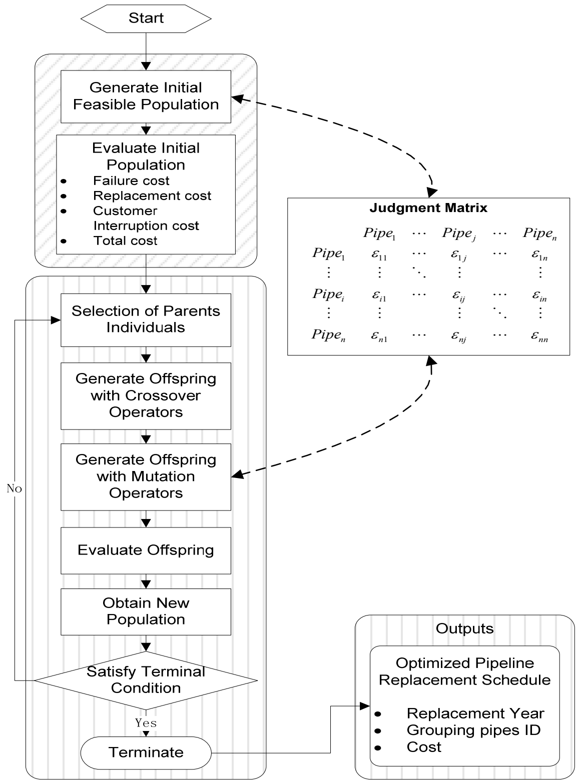

Fig 2 Flow Chart of Modified GA Model

The representation involves several 'genes' for each pipe of the network. The genes number is decided by the maximum number of pipes grouped with each pipe. Practically, the budget of water network utility generally is lower than 2 million AUD, which is the highest priority budget for replacements. This budget can do upward 20 mains replacement or as few as 5 or less. Therefore, it is reasonable to assume that the maximum number of pipes grouped is 5.

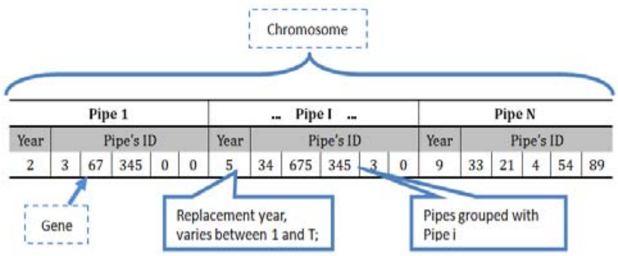

Fig 3: Encoding A Replacement Schedules Using A Chromosome

According to this assumption, the number of "genes" for each pipe is 6, which showed in Fig 3. It should be noted that the number of "genes" can be defined by user.

V. A CASE STUDY

A. Introduction

A section of a water distribution network, which served a community in south Queensland, Australia, was analyzed. Table I provides a sample of details about the water network. The network comprised 18818 pipes (total length of 87.7km) which were installed between 1950 and 2010, and served a population of nearly 50,000 inhabitants.

TABLE I. PIPELINE SUMMARY OF SELECTED AREA

Items	Description
Diameter (mm)	50, 63, 75, 80, 90, 100, 110, 150, 200, 220, 250, 300, 375, 411, 450, 500, 510, 525, 565, 590, 600, 660, 700, 750, 800, 850, 900
Material (5 types)	Asbestos Cement(AC), Cast Iron Cement Lined(CICL), Ductile Iron Cement Lined(DICL), Mild Steel Concrete Lined(MSCL), Unplasticized Polyvinyl Chloride (UPVC)
Length	From 0.1m to 866m
Zone area 4 types	RURAL (RUR), URBAN (URB), HIGH DENSITY URBAN (HDU), CBD

B. Assumptions

Some data and information (hydraulic data and expert knowledge) were not obtained by the researcher, therefore, "adjacent pipes" was only considered as a criterion in grouping method.

For this targeted water network, only replacement cost and repair cost were considered, because of a lack of social cost, direct and indirect damage cost information, which was alternated by adjustment factors given by network operators.

The annual budget for replacement of the whole water distribution network was two million AUD. Since, the selected area utilized in this case study was approximately 10% of its total network, it was reasonable to assume that the budget for the selected area was 200,000 AUD per year.

C. Preanalysis

Based on the pipeline repair historical data, in the selected area, there were 986 pipeline repair records from 2002 to 2010, with 5 different pipe materials. A Regression analysis [8] was to calculate repair cost of pipe i, based on equation:

$$C_i^{rep} = a + b \cdot D_i^c + d \cdot u_i^e + f \cdot D_i \cdot u_i \quad . \quad (15)$$

TABLE II. PARAMETERS FOR REPAIR COST EQUATIONS

Type of pipe	Diameter	a	b	c	d	e	R^2
AC CICL DICL UPVC	50mm – 450mm	877.201	0.066	1.849	0.233	-0.146	0.99
MSCL	300mm-900mm	659.143	0.023	2.063	-.002	19.399	0.89

In this case, decision variable u_i is the depth of the pipe buried, where 1 indicates the depth <= 1.5 meters, and 2 indicates the depth > 1.5 meters.

a, b, c, d, e, and *f* are coefficients estimated using regression techniques, and it is independent of pipe diameter, so parameter *f* is equal to 0; Cost equations for the repair costs of the following types of pipe are given in Table II.

Based on the history contract payments for the last year for water main replacements, a realistic cost of replacing water mains based on diameter is shown in Table III.

TABLE III. REPLACEMENT COSTS

Diameter Size of Pipe	Replacement Cost (AUD/m)
100mm	533
150mm	584
200mm-250mm	980
300mm	1150

It was assume that the machinery cost was not affected by different materials and diameters, therefore, it is taken as *M*=1000AUD/unit. The travel cost in this case, the constant value *CV*, which was a distance-unit cost, was equal to 100 AUD/km.

In this case study, a pre-analysis was done to screen target pipes from the 18818 pipes in the selected area. A well proved non homogeneous Poisson-based model [9], which is capable of considering time-dependent covariates, was used to forecast breakage rates, and found 439 target pipes using 986 historical records from 2002 to 2010. These 439 pipes were with high probability to failure in the future years and were selected as targeted pipes for further analysis. As the main purpose of the case study was to test the MGO model, the failure analysis is not reported here. Note that, the planning horizon considered in this case study was 20 years (*T*=20). For these 439 pipes, the total cost of each individual pipe in each planning year (from 1 to 21) was calculated, and 37 pipes were filtered, which minimum cost happened within the decision horizon.

D. Grouping analysis and Results

In the first step, the Judgment Matrix was calculated. In this case, the Judgment Matrix is a "37 multiply 37" Matrix with "0" and "1". Through that Judgment Matrix, grouping options with pipe ID for each pipe were understand. This is a problem-specific knowledge for produce improved offspring using in the modified GA model.

The second step was to run the proposed modified GA model, with utilizing Judgment Matrix as a criterion to evaluate the populations.

The Table IV shows the final result of various choices of grouping pipes for replacement scheduling. The label (1, 2, …, 37) indicates the pipe ID, and each number in each grid illustrates the year of corresponding pipe to be replaced. Each row indicates one replacement scheduling with one corresponding grouping option. The right column shows the total cost during the planning horizon 20 years with AUD.

The first row of that table shows the replacement scheduling without grouping pipes. The total cost will be up to 1,460,895 AUD. The following rows indicate the replacement scheduling with grouping pipes. For instance, in row 3, only pipe 26 and pipe 27 will be grouped as one replacement job in the second year, and the total cost will be 1,159,344 AUD, 11551 AUD will be reduced for that option, compared with non-grouping option. Searching by the modified GA model, the best option with minimum total cost during planning horizon 20 years is listed in the bottom row. It shows that pipe 5 and 6 can be grouped together replaced in the 3rd year; pipe 22, 23 and 24 will be united as one group replaced in the 4th year; pipe 25, 26 and 27 can be replaced in the 3rd year as a group; Pipe 29, 30, 31, 32 and 33 can be grouped and replaced in the 4th year; and pipe 36 and 37 can be replaced in the first year. The total cost of the optimum solution can be reduced to 1,273,212 AUD, which will save 187,683 AUD for a 20 years planning, approximately 12.85%.

TABLE IV. VARIOUS CHOICES OF GROUPING PIPES FOR REPLACEMENT SCHEDULING

	Pipe ID																				
Schedule	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**
1	*7*	*5*	*1*	*6*	*2*	*6*	*14*	*7*	*3*	*5*	*2*	*2*	*6*	*2*	*3*	*2*	*8*	*9*	*4*	*9*	*2*
2	*6*	*6*	*1*	*6*	*2*	*6*	*14*	*7*	*3*	*5*	*2*	*2*	*6*	*2*	*3*	*2*	*8*	*9*	*4*	*9*	*2*
3	*7*	*5*	*1*	*7*	*2*	*6*	*14*	*7*	*3*	*5*	*2*	*2*	*6*	*2*	*3*	*2*	*8*	*9*	*4*	*9*	*2*
…	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
Optimum	***7***	***5***	***1***	***6***	***3***	***3***	***14***	***7***	***3***	***5***	***2***	***2***	***6***	***2***	***3***	***2***	***8***	***9***	***4***	***9***	***2***

Schedule	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**	**31**	**32**	**33**	**34**	**35**	**36**	**37**	**Total Cost (AUD)**
1	*6*	*5*	*6*	*4*	*5*	*2*	*10*	*4*	*8*	*4*	*6*	*3*	*3*	*10*	*1*	*2*	1,460,895
2	*6*	*5*	*6*	*4*	*5*	*2*	*10*	*4*	*8*	*4*	*6*	*3*	*3*	*10*	*1*	*2*	1,358,120
3	*6*	*5*	*6*	*4*	*2*	*2*	*10*	*4*	*8*	*4*	*6*	*3*	*3*	*10*	*1*	*2*	1,359,344
…	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	……….
Optimum	***6***	***4***	***4***	***3***	***3***	***3***	***10***	***4***	***4***	***4***	***4***	***4***	***3***	***10***	***1***	***1***	**1,273,212**

VI. CONCLUSIONS

Grouping in planning replacement jobs for distributed water pipelines can effectively increase cost effectiveness if done properly. However, an applicable grouping method for pipeline maintenance is yet to be developed. To address this issue, a novel grouping model based on a modified GA is developed to find the optimum grouping option for replacement scheduling of pipelines. Three criteria including adjacent geographically distribution, identical replacement machinery and similar service interruption areas are proposed for effective pipe grouping.

An industrial case study based on a section of a real water distribution network was conducted to test the model. The results of the case study show that the optimally-grouped maintenance jobs using this grouping model can effectively reduce total cost compared with the maintenance without grouping pipes. Although only one criterion (adjacent geographically distribution) was considered in the case study due to the unavailability of data at the current stage, dramatic cost reduction was still achieved.

It is reasonable to anticipate that greater economic effectiveness can be acquired, when the other two grouping criteria are taken into account. The authors will test this hypothesis in the future research. This paper focuses on water pipelines. However, the developed grouping model can also be applied to other distributed assets such as electricity distribution networks, railway networks, and roads.

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